NASA-LRC PROGRAM TO DEFINE EXPERIMENTALLY THE EARTH'S IR HORIZON

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INTRODUCTION

This paper outlines the scope and present status of the Langley Research Center program for defining experimentally the earth's infrared horizon. The ultimate objective is to obtain flight measurements of the radiance signature of the earth's horizon which will provide basic information to design and evaluate the performance of infrared horizon sensors with a vertical determination accuracy to 0.01°. For these data to be useful for a wide range of space missions, they must include the deterministic and random horizon variations due to such parameters as geographical position, seasonal atmospheric variations, etc.

The program includes both flight experiments and analytical studies. The flight experiments include one conducted on the X-15 research aircraft where data were obtained in three intervals of the IR spectrum, and a second experiment called Project Scanner, which obtained measurements in two spectral intervals. The object of the current analytical study is to investigate the design and feasibility of a more comprehensive flight experiment to extend the data coverage beyond that provided by the X-15 and Project Scanner. This study is entitled "Earth Coverage IR Horizon Measurement Program (ECHMP)" although it is often referred to as "Horizon Definition Measurement Program (HDMP)."

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This paper will present a summary of the flight results obtained to date, including typical flight data samples. A summary of the ECHMP study results are also given with Langley's comments based on the data available.

Flight Experiments

The objectives of the flight experiments have been to obtain radiance profile measurements in the spectral intervals most promising for horizon sensor use, and to provide experimental verification of analytical IR radiance profile synthesis techniques.

X-15 Experiment

Details of the X-15 Horizon Radiometer flight experiment are shown schematically on figure 1. The radiometer illustrated conceptually on the left was flown in a tail-cone box on the aircraft and viewed the horizon by means of a motor-driven scan mirror. The radiometer consisted of a 5-inch aperture, F:1.0 optical system which focused the horizon energy through a filter onto the detector. The information necessary to position the measured radiance relative to the earth was obtained from a radiometer scan position output, a stable platform in the X-15, and ground tracking data. A more complete description of the system is contained in reference 1. The 0.13° field of view provided a radiometric definition of approximately 2 km at the horizon, and the positioning accuracy of the field of view was 5 km. Three flights of the X-15 were made, in the months of May, June, and July, representing summer conditions,

and data in a different spectral interval were obtained on each flight. The scattered and reflected solar energy in the 0.8 to 2.8μ spectral interval was measured on the first flight in July, 1964. On the second flight in May, 1965, the thermal energy from the earth and clouds as seen through the atmospheric "window" in the 10.5 to 13.5μ interval was measured, and the measurements of the thermal energy emitted from the atmospheric CO_2 and water vapor in the 14.0 to 20μ spectral were obtained from the third flight in June, 1965. Several attempts were made to collect additional data in the 14 to 20μ region under winter conditions; however, each was thwarted by a combination of bad weather and X-15 operational problems. No further X-15 flights are planned. Meteorological data from balloon and rocketsondes were collected for each flight and radiance profiles were generated by analytical means for comparison with the measured data.

Figure 2 shows a comparison of the measured and analytically derived profiles for Flight 3, which was in the 14 to 20μ spectral region. The "effective radiance" shown on the ordinate is radiance received by the detector through the spectral bandpass of the radiometer. The solid profile was obtained by averaging the data for all measured horizon crossings. The cross-sectioned area shows the boundaries containing all of the individually measured profiles. The dotted line is the theoretical profile* generated from the meteorological data.

The agreement between measurement and theory is seen to be excellent above 25 km where the primary contributor is atmospheric CO_2. The measurement

*The theoretical profile was generated for NASA by Dr. Wark and Mr. J. Alishouse of ESSA using the program described in reference 2.

and theory do not show the same agreement in the region below 25 km where the contribution due to atmospheric water vapor becomes appreciable. The prediction of water vapor mixing ratio as a function of altitude is difficult above approximately 8 km, and this factor is believed to be responsible for the variance.

The X-15 flight data in the other spectral intervals are not presented here; however, it generally verified the applicable theory, and thus substantiated the conclusion reached from analytical studies that the most promising spectral interval for horizon sensor use would be the 15μ CO_2 absorption band.

Project Scanner Experiment

The Project Scanner flight experiment is a suborbital ballistic rocket vehicle fired from Wallops Island, Virginia, to an altitude of 700 km. An operational schematic of the Scanner spacecraft is shown on figure 3. The spacecraft is despun to 3/4 rps when data-gathering altitude is reached, and is erected to the local vertical by a cold gas reaction jet system deriving information from a horizon sensor and rate gyro. Two radiometers are mounted back to back in the spacecraft, each having five detectors defining elemental fields of view vertically arrayed to measure radiance at different altitudes on the profile. Each elemental field of view is approximately 0.025° in the vertical direction by 0.100° in the horizontal plane which provides a 2 km vertical definition at the horizon. The radiometer fields of view are scanned through the horizon at 10° per second by a motor-driven mirror.

The precise attitude information needed to position the radiance data relative to the earth is obtained by means of a celestial mapper

which detects star transits as the mapper axis is scanned through the celestial sphere by the spacecraft spin. All spacecraft data are transmitted to earth on a real-time basis and later combined with ground tracking information to reconstruct the measured horizon radiance profiles. The spacecraft spin also provides an azimuth scan of the radiometer line of sight which provides horizon crossings over the geographical area (or "footprint") shown on figure 4. All of the measured profiles are contained within the annulus bounded by the concentric rings. Two Project Scanner flights have been obtained, Flight 1 being in August 1966 with summer atmospheric conditions, and Flight 2 in December 1966 for winter atmospheric conditions. Extensive meteorological data were obtained within 3 hours of each flight so that analytical profiles could be derived for comparison with the measured data. The Meteorological Rocket Network (MRN) stations which cooperated to provide the high-altitude data for the Scanner Project are shown on figure 4, with the stations supplying data for Flight 1 marked with a vertical bar.

The data from Flight 1 are presently being reduced; however, several profiles are available. Figure 5 shows a comparison between a CO_2 horizon radiance profile measured in the southern portion of the footprint (near Antigua) and a profile analytically synthesized for the same spectral interval as described in references 4 and 5 using the meteorological data obtained at the time of the flight. The Project Scanner CO_2 band is the wave-number band 615 to 715 cm^{-1} (14.0 to 16.3μ) at the half-power points of the spectral response. The measured CO_2 profile, shown as a solid curve,

was obtained by averaging the outputs of four elemental detectors for each tangent height during the horizon crossing, and plotting the smoothed curve which has the effect of improving the radiometric signal to noise. Also shown on figure 5 are the error boundaries conservatively estimated for the measured profile. The cross-hatched area bounding the profile illustrates the root-mean-square (1-sigma) error magnitude associated with the radiometric signal to noise as received on the ground tape, tape reading error, etc., and also includes a random error of approximately 1 km in the measurement of line-of-sight position. Other errors which exist in the measurements such as uncertainties in radiance calibration and in the Starmapper - radiometer alinement, are not random for a single flight, and hence create the effect of a bias on any single profile. An estimate of the magnitude of these errors is shown by the box on figure 5, and corresponds to a radiance calibration error of ± 5.5 percent full scale, and Starmapper alinement error of ± 1.5 km. The inner cross-hatched box corresponds to the random errors previously discussed. The uncertainties in the analytical profile due to meteorological data inaccuracies are not shown; however, they are estimated to have the effects of a tangent height uncertainty of +0.5, -2.0 km at the 3.0 watt-m^{-2}-sr^{-1} level, or of a radiance uncertainty of +0.05, -0.15 watt-m^{-2}-sr^{-1} for the peak radiance condition. Figure 6 shows a comparison between a profile measured in the northern portion of the footprint near Goose Bay, Labrador, and an analytical one generated from the meteorological data for that area. The fact that the measured and

analytical data agree so well for both profiles demonstrates that the profile synthesis program is accurate within the measurement uncertainties of the Scanner data.

Figure 7 shows the two analytical horizon radiance profiles from the preceding figures on the left, although the ordinate and abscissa have been interchanged. The atmospheric temperature profiles on which they are based are shown on the right. Note that the northern profile has a higher peak radiance than the southern. The reason for this, evident in the temperature plot to the right, is the much colder tropopause temperatures in the south. This is a feature typical of the summer atmosphere at the lower latitudes. Note also the sharp feature in the southern temperature profile near 30 km altitude. The horizon radiance profile shows the effects of this temperature feature at a slightly lower altitude.

The Project Scanner radiometer spectral response for the water vapor region covered the 315 to 475 cm^{-1} wave-number band (or 21.0 to 31.7μ) at the half-power points. The measured profiles presented for this spectral interval were obtained from a single detector. Figure 8 shows a comparison between a water vapor profile (solid line) measured near Antigua, B.W.I., and an analytical profile for the same region. The difference in slope between the measured and analytical profiles in the 8 to 15 km tangent height region is the most striking feature. The analytical profiles for the water vapor region are more uncertain than those for the CO_2, due to the fact that the water vapor mixing ratio for the atmosphere is highly

variable as a function of both altitude and time, while the CO_2 mixing ratio is nearly constant at all altitudes above 2 km. Measurements of the water vapor mixing ratio above 10 km altitude are not available from either balloonsonde or rocketsonde data, hence it was necessary to extrapolate from the low-altitude data to the heights covered by the profiles. The difference in slope seen on figure 8 may be due in part to the estimated mixing ratio used to synthesize the analytical profile; however, the close agreement shown in the tangent height regime above 15 km and at the peak radiance point indicates that other factors may be involved. The slope of the analytical profile is steeper than was anticipated early in the program, so one such contributing factor may be the 80 Hz high-frequency cutoff in the radiometer electronics.

Figure 9 shows a comparison between two radiance profiles measured in the eastern part of the footprint. One profile was obtained from a region clear of localized cloud conditions (solid line) and is marked "Clear." The dashed profile encountered a highly localized disturbance and is marked "Cloud." The azimuth scan apparently swept the field of view across a localized cloud condition during the radiometer down scan which gave the effect shown, where the cloud appears to affect only a restricted tangent height region (+12 km to -8 km). The effect of the cloud in this case was to reduce the radiance by a factor of almost 2 below approximately 10 km tangent height. Evidence of such local weather effects was noted on the water vapor channel throughout the flight, while no effects of significant magnitude were evident in the CO_2 channel.

The experimental measurements from Project Scanner just discussed must be considered preliminary since there has been little opportunity for analysis of the results in depth. However, several conclusions are justified.

1. The 15μ CO_2 band is superior to the water vapor band for horizon sensor use due to the reduced effects of clouds and local weather anomalies.

2. The measurements obtained in the 15μ CO_2 band verify the radiance profile synthesis techniques employed within Project Scanner measurement accuracy. The synthesized radiance profiles may therefore be used to 50 km tangent heights with confidence where meteorological data are available.

3. The analytical profile synthesis technique is a powerful tool for studying design approaches to, and accuracy of, high precision horizon sensors, since it may be used in lieu of experimental data for generalized cases.

Analytical Studies

The footprint shown on figure 4 represents the widest geographical coverage provided to date by a flight experiment obtaining data of a quality useful for horizon definition. When it is also realized that the data period lasted for less than 15 minutes, the inadequacy of the test for statistical purposes becomes apparent. LRC therefore set out to establish a baseline design for an experiment to extend the coverage to a global basis, and to obtain sufficient data to ascertain the deterministic

and random variations of the radiance profile as a function of geography and season. For this purpose a two-part study contract was awarded to Honeywell, Inc., which was restricted to the 15μ CO_2 region.

The goal of the first part was to determine the flight data requirements to meet the desired experiment objective by answering the following questions:

1. What are the important factors which shape the 15μ horizon gradient, and what form of analytical model based on these factors will describe the gradient with sufficient accuracy for precise horizon sensor studies?

2. What are the deterministic and random variations of the horizon as sensed by a horizon scanner due to season, geographic position, etc.?

3. What are the experimental measurement requirements to verify the estimated deterministic and random variations?

4. What are the general characteristics of a cost-effective flight system to meet the estimated data requirements?

The second part of the study has the goal of determining the feasibility of building and flying a spacecraft system to obtain the estimated data. To do this a preliminary conceptual design was specified based on the most cost-effective flight system for a study to:

1. Determine the mission profile requirements.

2. Establish the trade-offs available in designing a spacecraft/launch-vehicle/ground-support system.

3. Expose the technological areas where development problems were likely.

The first part of the study was completed in October 1966 and provided several significant results. For example:

A profile synthesis technique was developed for use in the 15μ CO_2 region. The most important variables affecting gradients in this spectral region were verified to be the atmospheric temperature and pressure profiles, and the synthesis technique included the effects of doppler broadening and local thermal nonequilibrium, and is believed accurate to 80 km tangent heights. The transmittance data utilized in this model are derived from Plass (Reference 3) and cover the spectral region 600 to 725 cm^{-1}. The program allows the spectrum to be divided into either 10 or 25 spectral intervals as required to predict accurately the effects of radiometric spectral filter functions on the profile. The development of this technique is described in reference 4 and the computer program for implementing it is given in reference 5. The program was used to synthesize the profiles shown for Project Scanner in figures 5 through 7, and so has been experimentally verified within Scanner accuracy.

The profile synthesis technique was applied to a meteorological body of temperature and pressure data (reference 6) spanning the North American continent and covering a 1-year time period. The resulting profiles (reference 7) were used to determine the variations in the horizon as detected by several types of horizon sensors. These results are reported in reference 8 and are also available in more detail in reference 9. In summary, they indicate that horizon sensor accuracies of 0.01° to 0.02° appear feasible in the 15μ CO_2 band for satellites in the 200-500 n.m. altitude range, and that the more accurate horizon sensors operate on the higher tangent height portions of the radiance profile. Since the accuracy of the meteorological data compiled for the Part 1 study is poorest in the higher altitude regime

due to the paucity of available meteorological soundings, further effort will be necessary to verify the accuracy estimates obtained.

Statistical investigation of the horizon sensor study results indicated that the horizon variance is correlated with both latitude and time of year, showing that significant deterministic effects exist. For example, the study performed on temporal variations yielded the results shown on figure 10. The detected horizon variations for one latitude were fitted to a Fourier series model of the yearly cycle. Figure 10 shows the residual standard deviation as a function of the harmonic terms considered by the model. It is seen that the residual decreases as the model is expanded to the sixth harmonic. Similar studies were performed to examine latitude and longitude variations for a fixed time. The latitude variations clearly show the existence of a third harmonic fit and indicate that higher harmonics are present, probably to the sixth. A much weaker correlation of horizon variances with longitude was indicated, with the result that further data must be obtained to define the effect.

From the preceding results, data requirements were deduced for the geographical area represented by the meteorological sample. It was then necessary to extrapolate the data requirements from the sampled area to cover the earth. The results of this extrapolation are shown on table 1. The latitude spacing, time cells, and number of samples per cell were selected from the statistical studies previously mentioned. The cell spacing in longitude, beyond the area covered by the meteorological sample, was derived from knowledge of the placement and extent of typical seasonal

circulation patterns (e.g., Winter Aleutian anticyclone, etc.) and from Tiros VII data on effective stratospheric temperature. The spacing obtained over the Horthern Hemisphere was used symmetrically in the Southern Hemisphere. Note that the sampling requirements per space cell increase with latitude due to the increasing variance found at the higher latitudes. The resulting requirement is approximately 55,000 profile samples per hemisphere or 110,000 samples total. These data are given in more detail in reference 10.

Another result of the Part I study was the indication of a cost effective flight system to obtain the data. The system concepts investigated included suborbital probes, spin-stabilized satellites, earth-pointing satellites, and manned spacecraft. The recommended system was a spin-stabilized, rolling wheel satellite in a near-polar, sun-synchronous orbit with passive radiometers for radiance measurement, and celestial mappers for attitude determination. The reliability considerations indicate that more than one satellite will be required for a 1-year lifetime.

Part II of the study was initiated to investigate the feasibility of developing a flight system to obtain the experimental profile measurements. The flight system being studied is the spin-stabilized, rolling wheel satellite which appeared most efficient in the Part I study. The design incorporates two radiometer channels and two attitude-determination sensor systems, primarily for redundancy. The feasibility analysis of this system is incomplete at this time; however, a status report may be of value.

The mission profile studies indicate that a 3 o'clock sun-synchronous orbit is most desirable since it provides the geographical coverage required, and also obtains measurements of the radiance profile at the times when diurnal atmospheric temperature variations are near a maximum. This orbit also allows efficient use of solar panels for spacecraft power purposes.

The technological areas where the most severe development problems appear are indicated on table 2. The present estimates of the dynamic range and accuracy requirements for the radiometric subsystem are seen to be severe and will require the use of a cooled detector. The detector cooling system for a long-duration mission requires development effort prior to entering a spacecraft fabrication effort. Design of the radiometer and calibration systems to meet the Precision and Calibration Repeatability requirements will also require advance development work.

The Spin-Angle (or roll position) attitude determination accuracy of ≤ 15 arc seconds will be difficult to achieve from celestial measurements obtained from a spinning spacecraft. The difficulty is primarily in the generation of an accurate time history of the spacecraft spin position from the individual star sightings. An accurate analytical model of the perturbed vehicle motion is required for this task, and the description of the perturbations is presently being investigated in detail.

The remaining spacecraft and ground systems appear feasible at this point. The study is scheduled to continue until May 1967; therefore, the preceding comments must be considered tentative.

In summary, the Earth Coverage IR Horizon Measurement Program study has documented a horizon radiance profile synthesis program which was verified by Project Scanner flight results, and compiled a bank of meteorological data which represent the yearly atmospheric changes for the North American portion of the Northern Hemisphere. The study results also indicate:

1. That horizon sensor accuracies of 0.01° to 0.02° are feasible in the 15μ CO_2 band.

2. That significant deterministic effects exist in the radiance profile due to season and latitude, and to a lesser extent, longitude.

3. A measurement program to define experimentally the earth's horizon will require approximately 110,000 profile samples taken over a 1-year span.

4. The radiometric subsystem requirements for such a measurement program will require advancement of existing technology in the areas of cooling systems for IR detectors and calibration of radiometric devices.

Concluding Remarks

The reduction of Project Scanner flight data will be continued, and the analysis techniques developed in the ECHMP study will be applied to these data. A preliminary report on Scanner flight results is tentatively scheduled for late summer 1967.

The feasibility study for an Earth Coverage IR Horizon Measurement Program will be continued and is scheduled for completion by June 1967. The results of this study will be published as NASA contractor reports when they are available.

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Table 1
Flight Data Sampling Requirements
Earth Coverage IR Measurement Program

Latitude Range	Time Cells per Year	Number of Space-Time Cells per Hemisphere	Number of Samples per cell	Northern Hemisphere Samples
0° - 20°N	13	442	16	7072
20°N- 30°N	13	234	16	3744
30°N- 60°N	13	1404	16	22464
60°N- 80°N	13	468	38	17784
80°N- 90°N	13	104	38	3952
		Total Samples - Northern Hemisphere		55016
				X 2
		Total Sampling Requirement Earth Coverage		110032

Table 2
Technology Areas Requiring Development
for Earth Coverage IR Horizon Measurement Program

Subsystem	Measurement Characteristic	Requirement	Comments
Radiometric	Dynamic Range	7×10^{-2}	Required cooled detector. Cooling system for long duration mission must be developed.
	Minimum Detectable Radiance	$0.01\ W\text{-}M^{-2} - SR^{-1}$	
	Precision	$\leq$ 0.15% Full Scale	Calibration Techniques and components must be developed for required accuracy
	Calibration Repeatibility (Inst. to Inst.)	1.0% Full Scale	
Attitude Determination	Spin Vector Orientation (pitch-yaw)	0.3°	Requires accurate celestial mapper and analytical model of spacecraft motion.
	Spin Angle	$\leq$ 15 sec.	

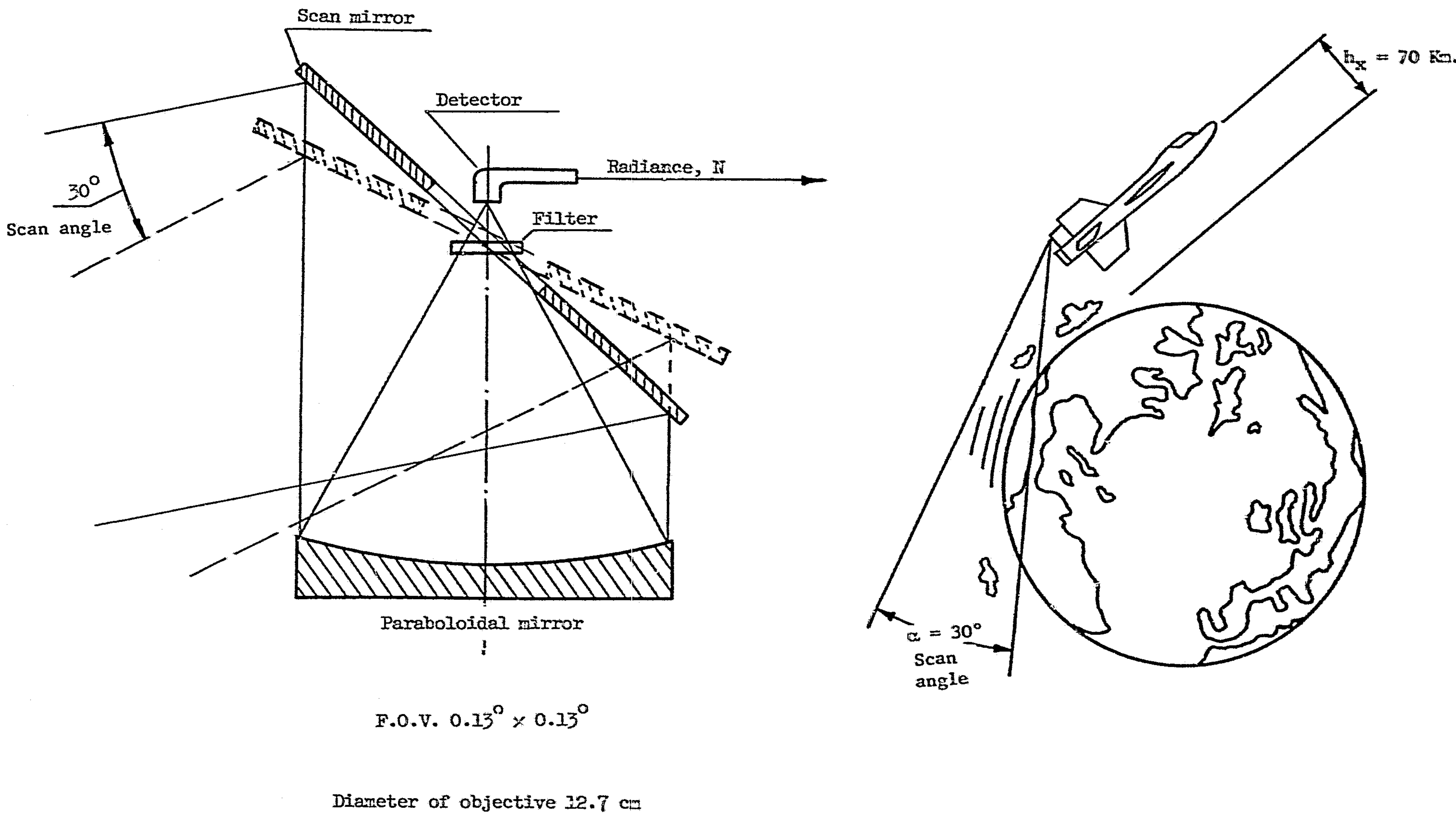

Figure 1: X-15 Horizon Radiometer Flight Experiment

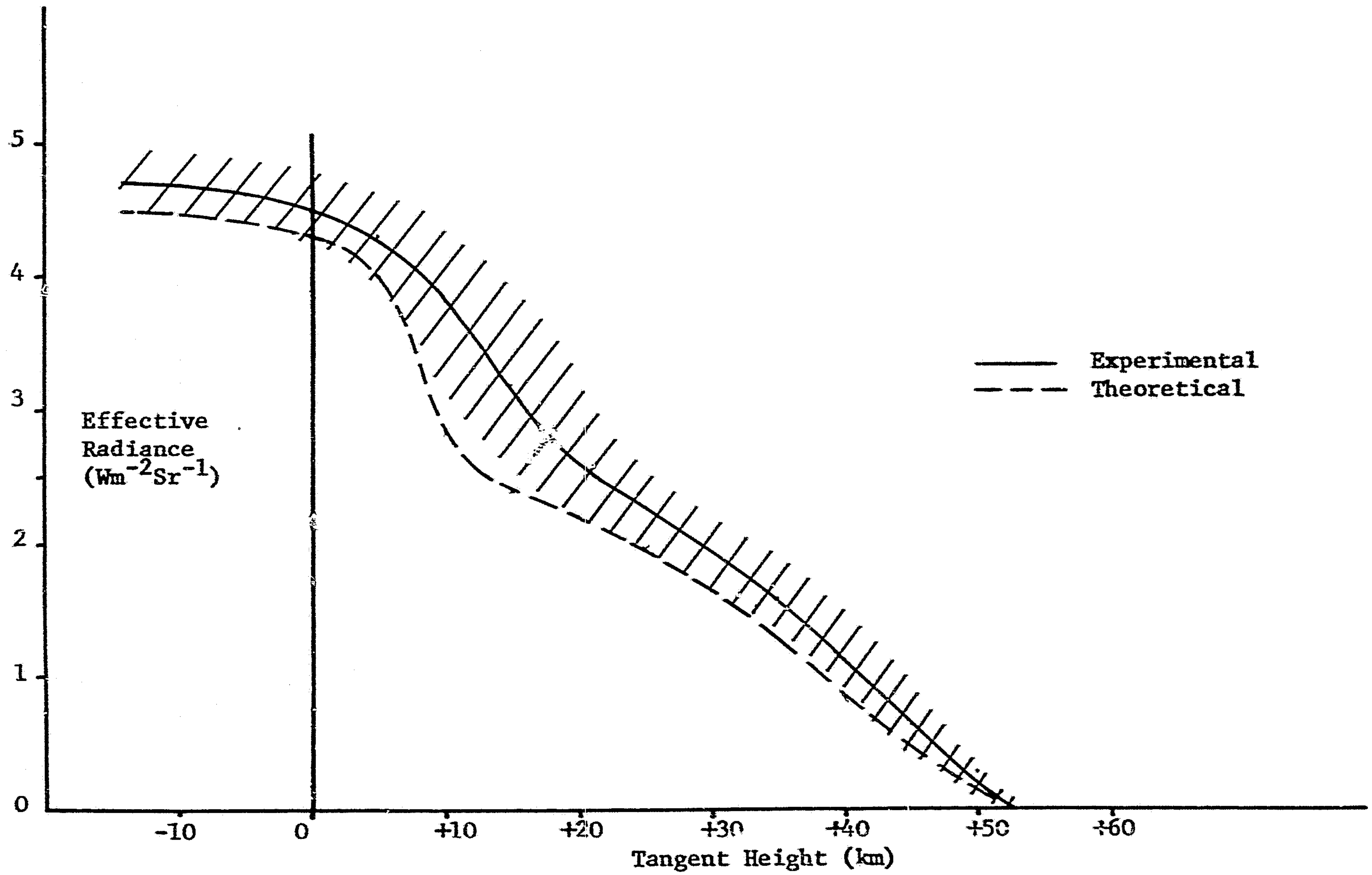

Figure 2: X-15 14-20μ Radiometer Flight Results

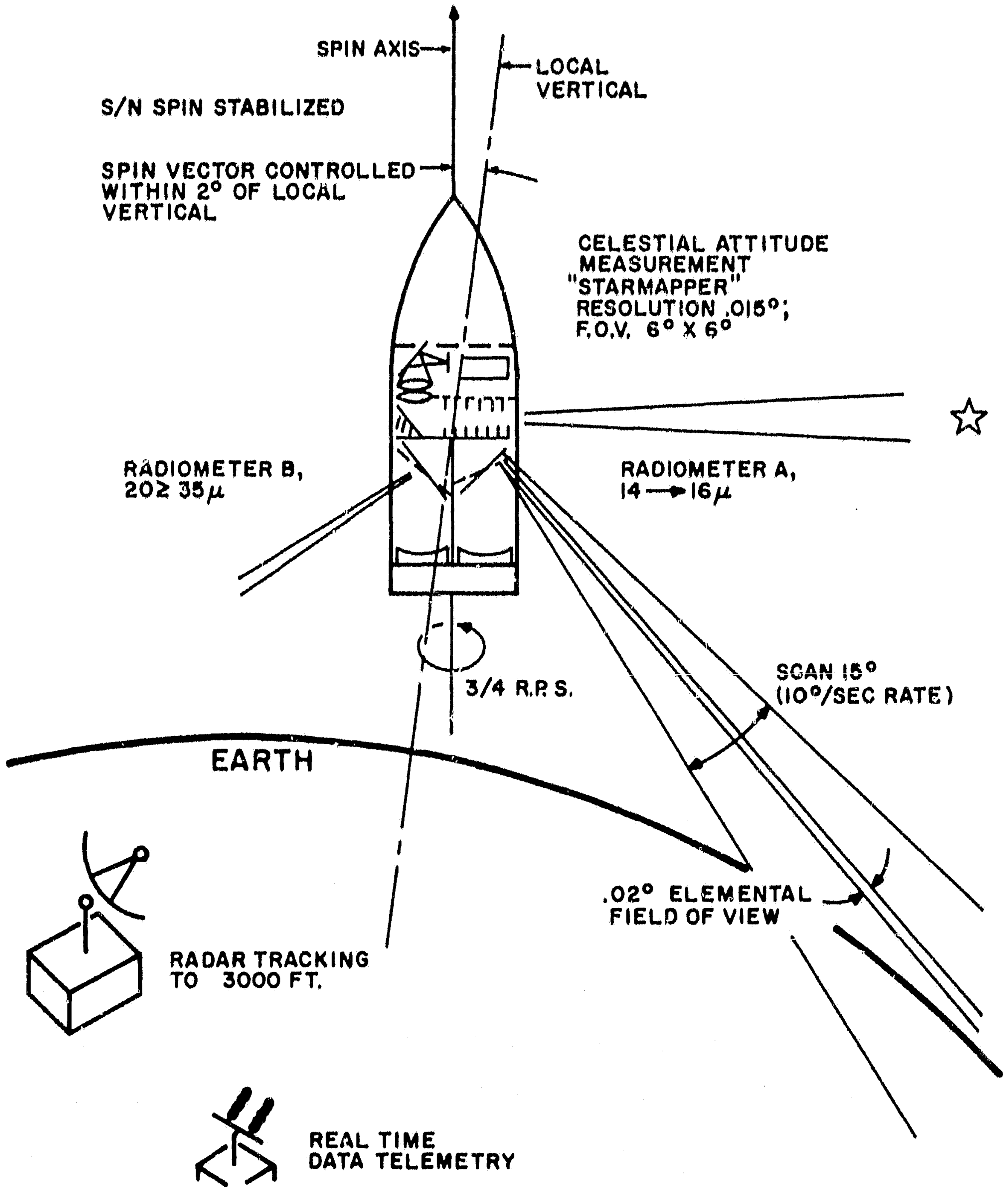

Figure 3: Scanner Spacecraft Operational Schematic

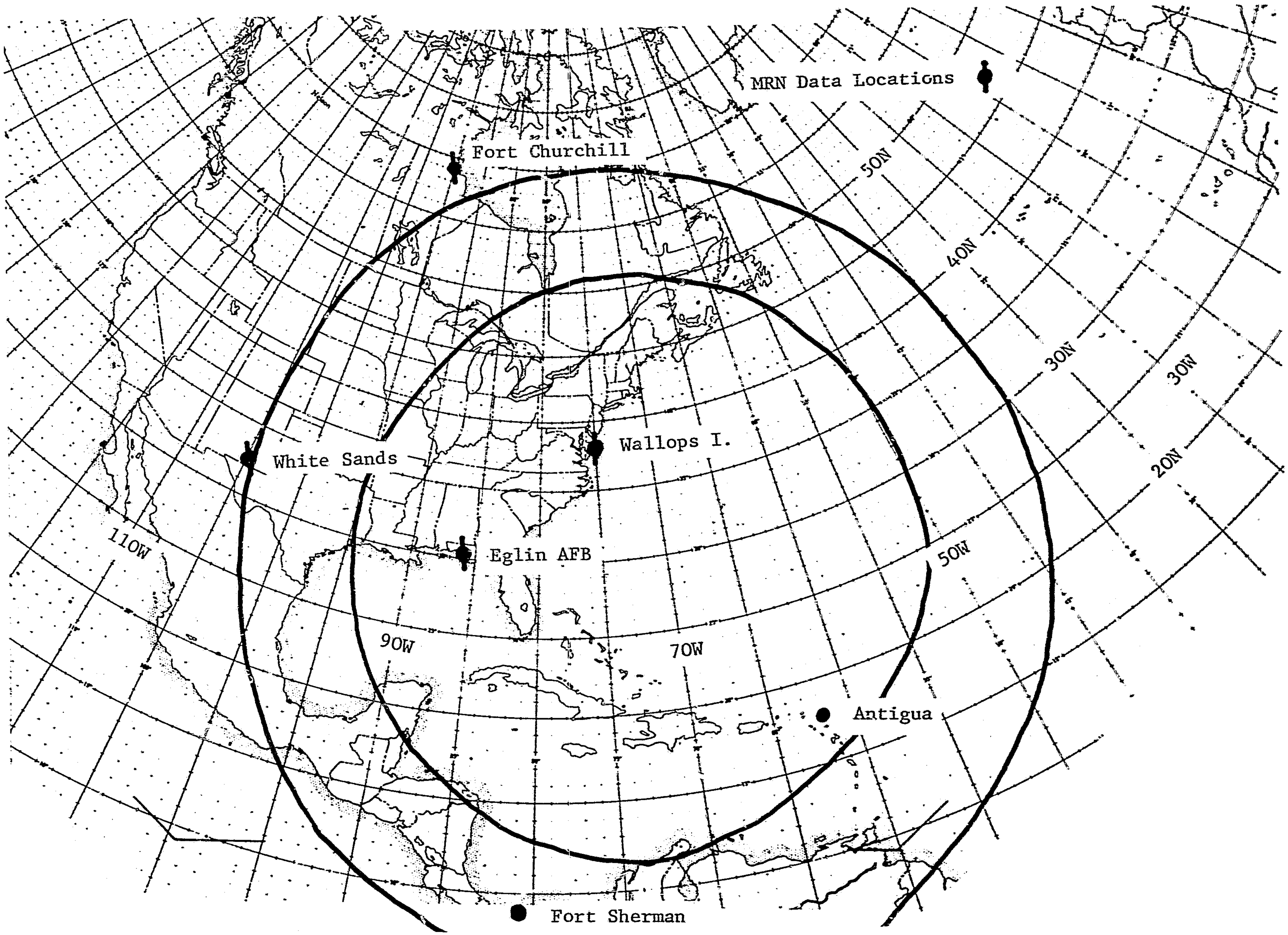

Figure 4: Project Scanner Geographical Coverage

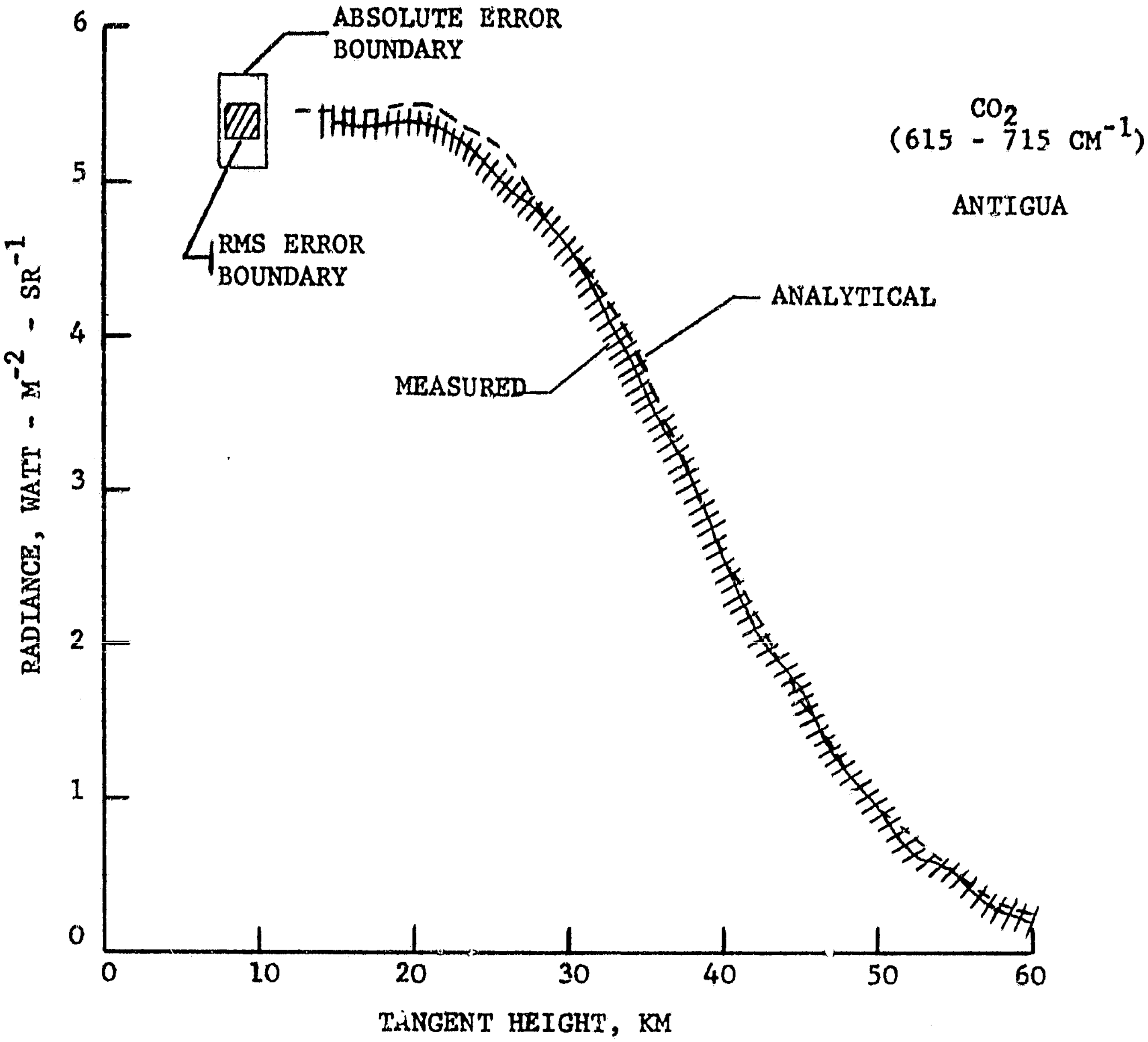

Figure 5: Comparison of measured and analytical CO_2 horizon profiles - Antigua

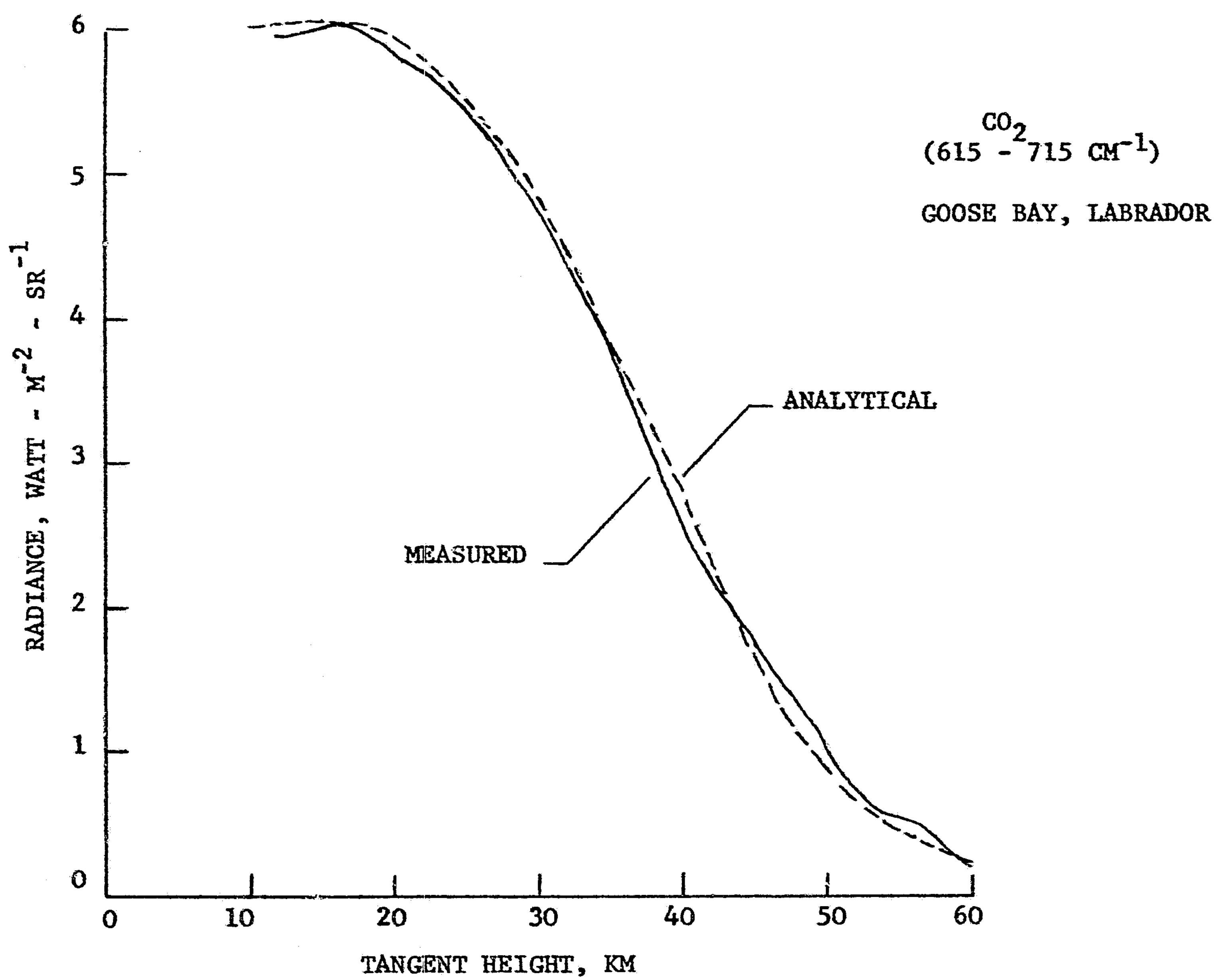

Figure 6: Comparison of measured and analytical CO_2 horizon profiles - Goose Bay

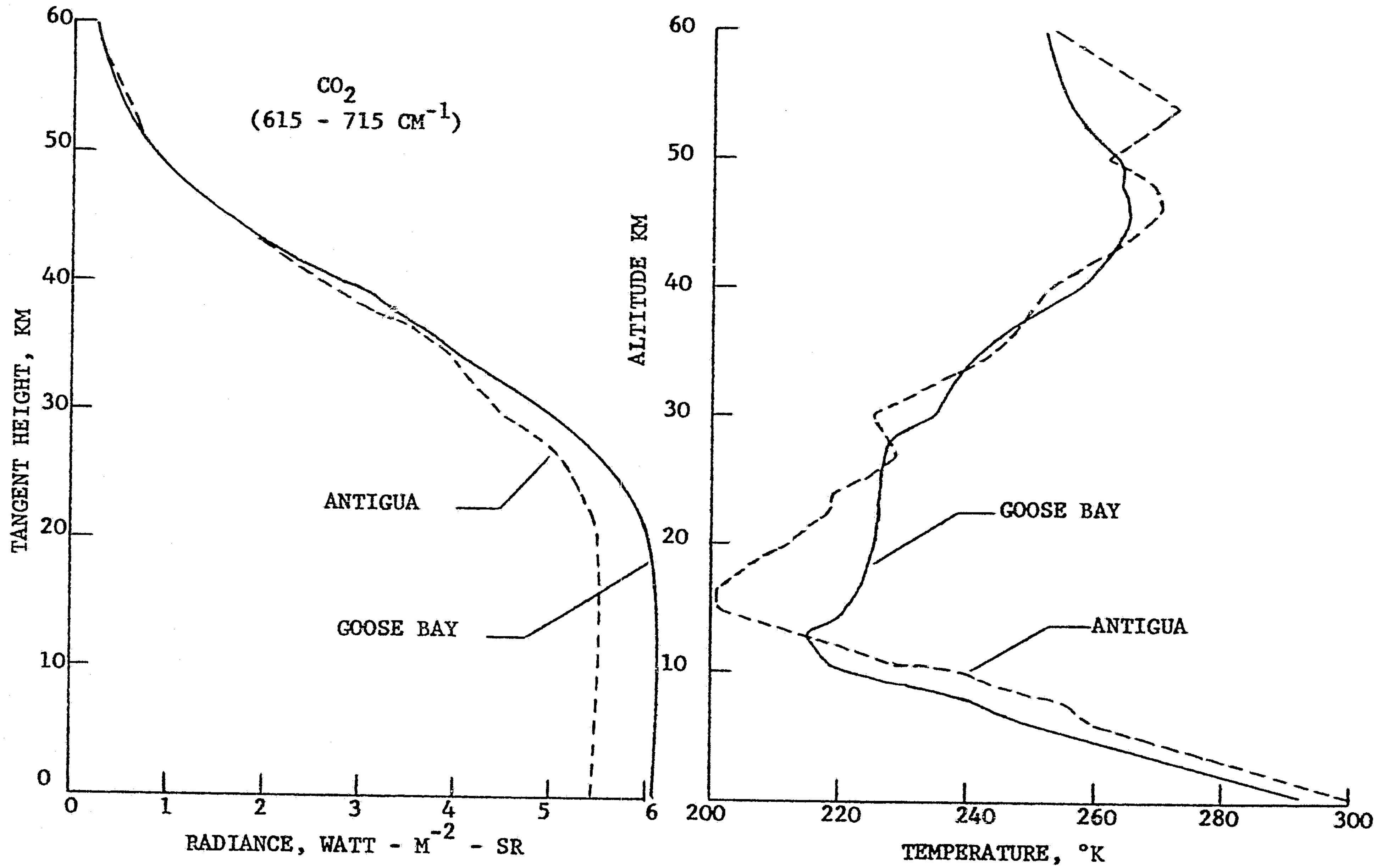

Figure 7: Comparison of northern and southern analytical CO_2 horizon profiles - August 16, 1966

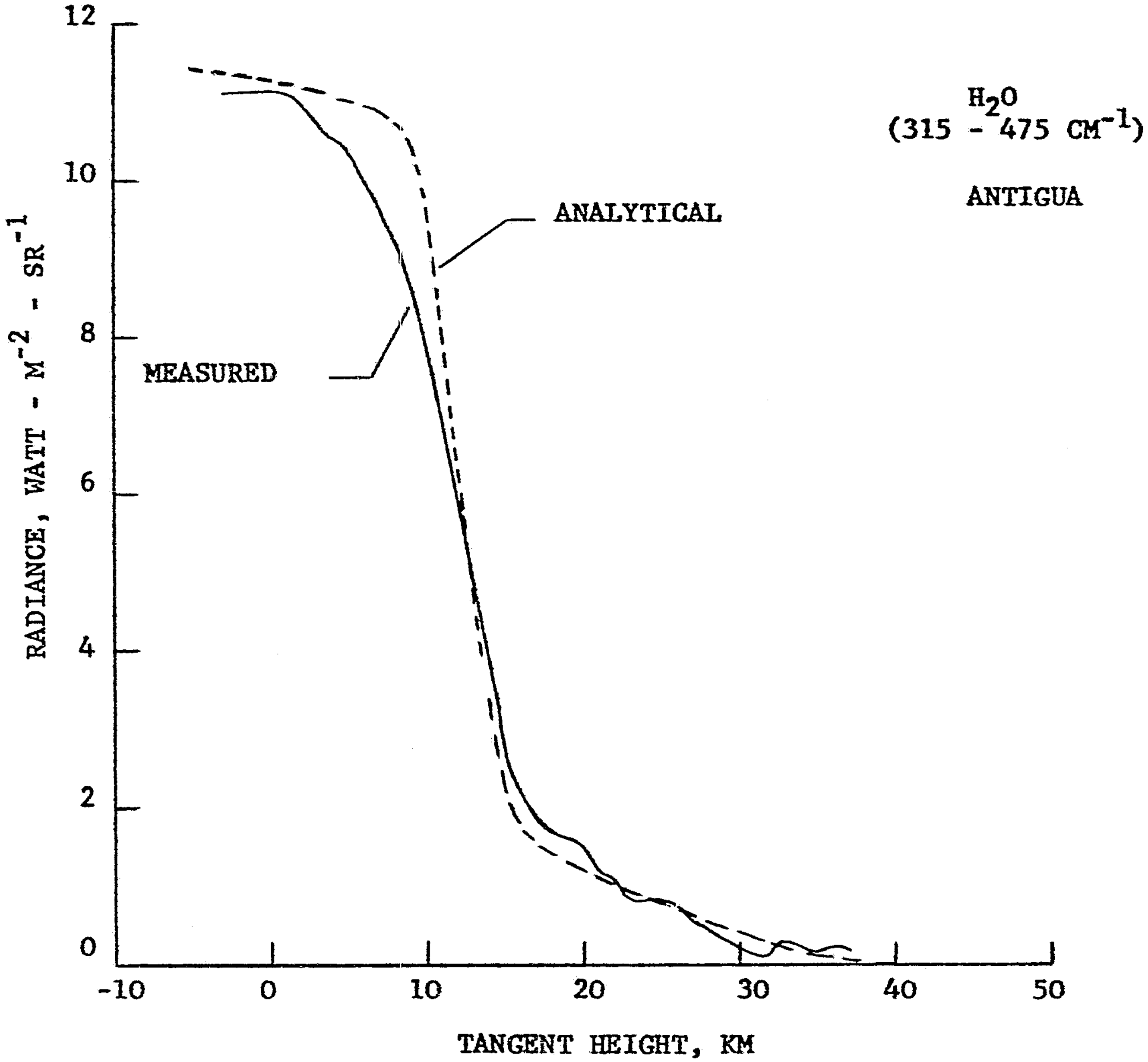

Figure 8: Comparison of measured and analytical H_2O vapor horizon profiles - Antigua

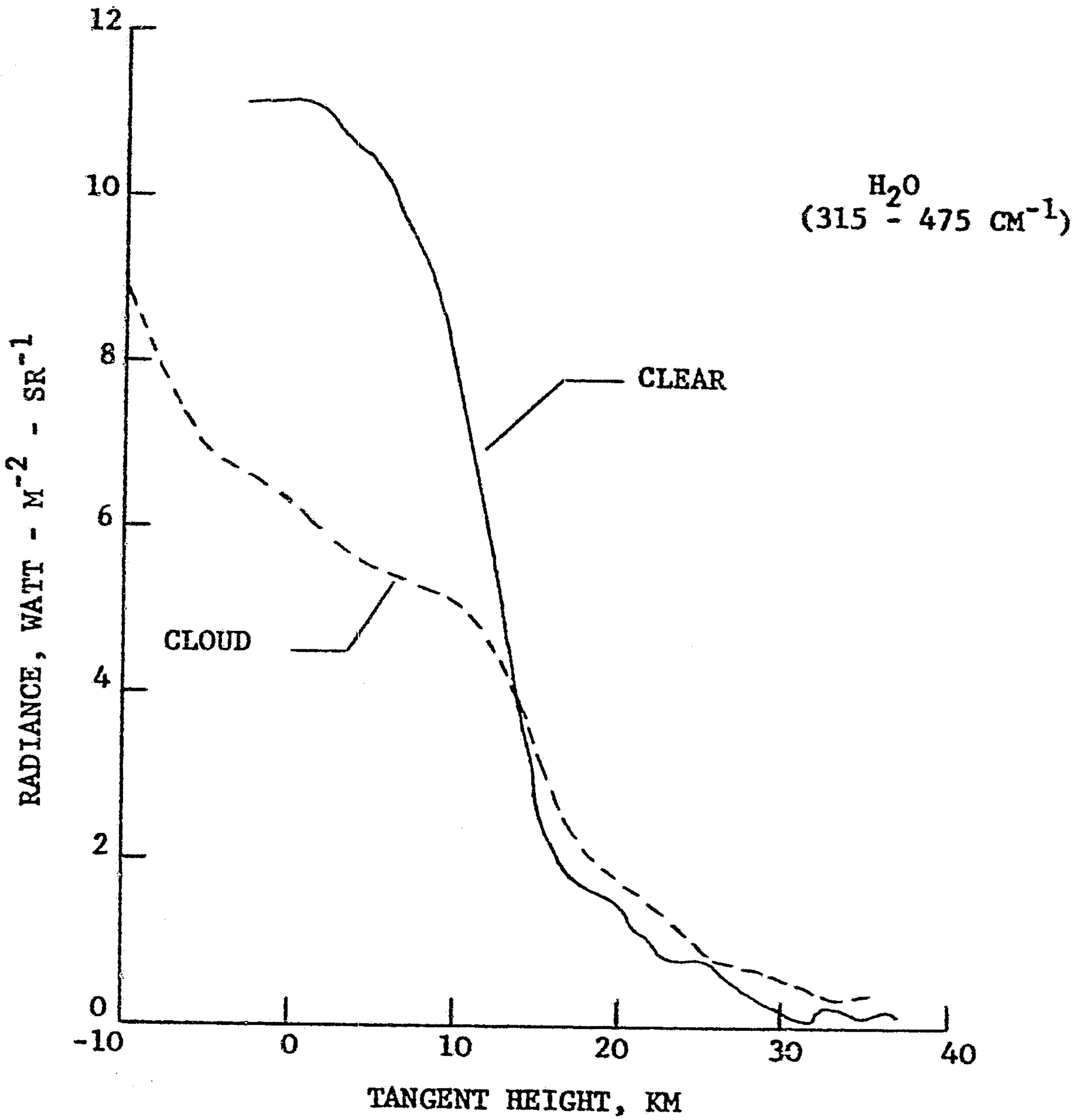

Figure 9: Comparison of two measured H_2O vapor horizon profiles showing effects of weather.

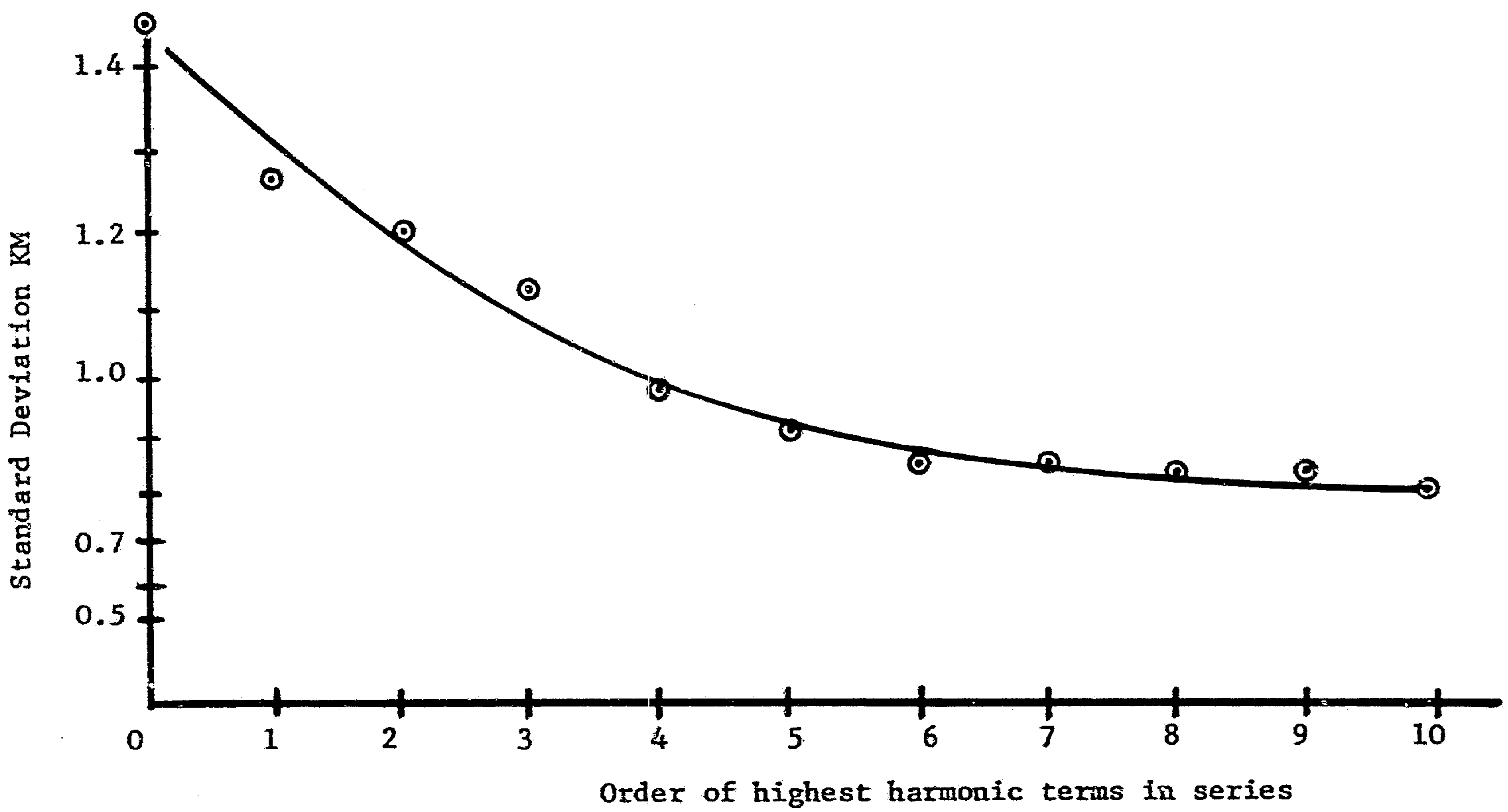

Figure 10 - Reduction in residual standard deviation of CO_2 horizon variances as seasonal deterministic effects are considered.